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Investigation on Mathematical model of two Phase (One phase is Newtonian and other is non-Newtonian) Coronary blood Flow in Capillary during Angina

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Abstract-
This study focuses on the behaviour of blood flow through capillaries during Angina. There are two layers in capillaries one is plasma layer and other layer is Red blood cells which is kwon as core layer. Plasma layer is Newtonian and Core layer is non – Newtonian. We applied Non-Newtonian power-law. Here blood is represented as Power law fluid model and flow model is shown by the equation of motion and the continuity equations. Using appropriate boundary conditions, numerical expression for volumetric flow rate and blood pressure drop have been derived. The role of hematocrit is explicit in the determination of blood pressure drop in the case of angina. The overall presentation is in tensorial form and solution technique adapted is analytical as well as numerical.

Keywords-
Two phase blood flow, Coronary blood flow ,coronary circulation, Angina, Plasma layer, Core layer, Hematocrit, Power-law Model, Non-Newtonian, Blood Pressure Drop, Behaviour of blood.

1. Introduction

1.1- Structure & Function of Heart

The human heart is a muscular organ containing four chambers that is situated just to the left of the midline of the thoracic cavity. I The upper two chambers (**atria**) are divided by a wall like structure called the interatrial septum. The lower two chambers (**ventricles**) are divided by a similar structure called the interventricular septum [2].

Blood flow through the heart is shown in figure-1 Blood that is low in oxygen flows into the right atrium from the veins known as the **superior vena cava** and **inferior vena cava.** The superior vena cava carries blood from the remainder of the trunk and the legs. Blood in the right atrium then flows through the right atrioventricular (tricuspid) valve into the right ventrical. The pulmonary circuit deoxygenated blood flowing into the right and left pulmonary arteries and their smaller branches. The blood becomes oxygenated while moving through the lungs capillary beds. Also in this part of the system carbon dioxide is released. [3]

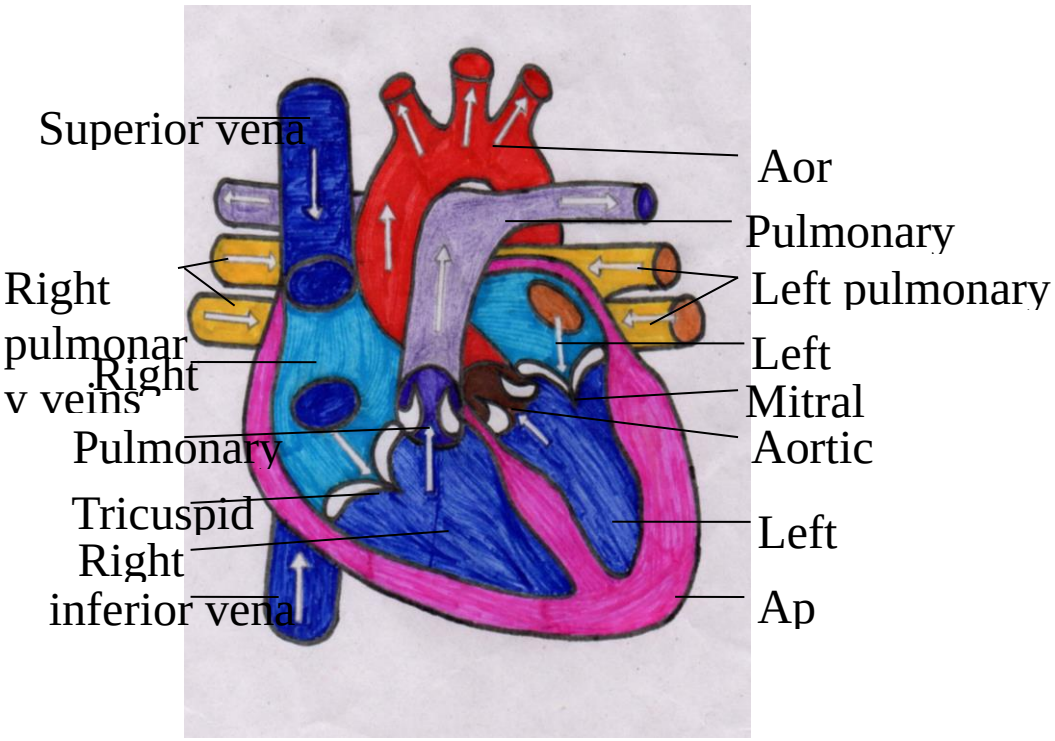


Fig. 1.1

Structure and Function of capillaries-

Capillaries are the smallest of a body's blood vessels that make up the microcirculation. Their endothelial linings are only one cell layer thick. These micro vessels, measuring around 5 to 10 micrometres (μm) in diameter, connect arterioles and venules, and they help to enable the exchange of water, oxygen, carbon dioxide, and many other nutrients and waste substances between the blood and the tissues[4] surrounding them. Lymph capillaries connect with larger lymph vessels to drain lymph collected in the microcirculation.

From the arterioles, blood flows into the smallest vessels of all, capillaries. Capillaries represent the junction between arteries and veins and start after the arterioles. Their wall consists of only one layer of cells that is called endothelium. This is to make easier the gas exchange between blood cells and tissues (blood → O2 → tissues → CO2 → blood) and also the exchange of metabolic products. Blood removes metabolic wastes from the tissues and supplies them with nutrients, achieving this with the help of two kinds of pressure: the hydrostatic pressure, which pushes water and nutrients out at the beginning of the vessel and the osmotic pressure that helps the water and the wastes enter within the vessel at its venous end.

The capillaries are very important. They are known as "exchange vessels" because it is here that the exchange of nutrients and wastes occurs.

1.3 -Coronary Circulation-

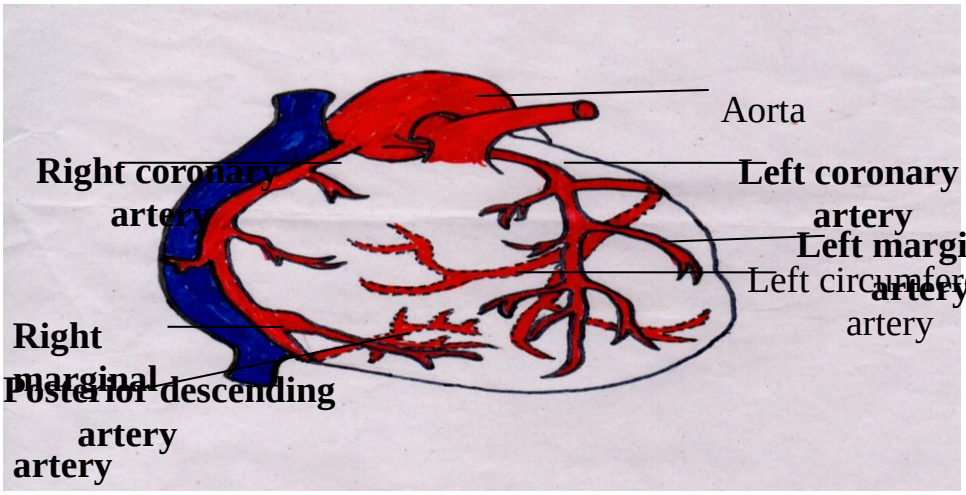


Fig. 1.3 Coronary Circulation

As the left and right coronary arteries run on the surface of the heart, they can be called epicardial coronary arteries. These arteries, when healthy, are capable of autoregulation to maintain coronary blood flow at levels appropriate to the needs of the heart muscle. These relatively narrow vessels are commonly affected by atherosclerosis and can become blocked, causing angina or a heart attack. The coronary arteries that run deep within the myocardium are referred to as subendocardial.
The coronary arteries are classified as "end circulation", since they represent the only source of blood supply to the myocardium; there is very little redundant blood supply, which is why blockage of these vessels can be so critical.

1.4- Constitution of blood-

Blood is a complex fluid consisting of particulate solids suspended in a non- Newtonian fluid. The particulate solids are red blood cells {RBCs},white blood cells {WBCs} and platelets. The fluid is plasma, which itself is a complex mixture of proteins and other intergradient in an aqueous base 5O% of plasma and 45% of the blood cells and 45% of the blood is RBCs and there is a few parts of the other cells. Which are ignorable So one phase of the blood is plasma and second phase of the blood is RBCs. Two phase coronary blood flow is study of measuring the blood pressure if hemoglobin known. The percentage of volume covered by blood cells in the whole blood is called hematocrit .

1.5- Angina-

Angina is chest pain or discomfort that occurs if an area of your heart muscle doesn't get enough oxygen-rich blood. Angina may feel like pressure or squeezing in your chest. The pain also can occur in your shoulders, arms, neck, jaw, or back. Angina pain may even feel like indigestion. Angina isn't a disease; it's a symptom of an underlying heart problem. Angina usually is a symptom of coronary heart disease (CHD). CHD is the most common type of heart disease in adults. It occurs if a waxy substance called plaque (plak) builds up on the inner walls of your coronary arteries. These arteries carry oxygen-rich blood to your heart. Plaque

Types of Angina

The major types of angina are stable, unstable, variant (Prinzmetal's), and microvascular. Knowing how the types differ is important. This is because they have different symptoms and require different treatment.[6]

2. - Real Model-

2.1 – Choice of frame of Reference

We select generalized three-dimensional orthogonal curvilinear co-ordinate system, briefly prescribed as E^3 , called as 3-dim Euclidean space, We interpret the quantities related to blood flow in tensorial form which is comparatively more realistic, The biophysical laws thus expressed fully hold good in any co-ordinate system , which is compulsion for the truthfulness

of the law Now , let the co-ordinate axes be OX^i where O is origin and superscript i = 1,2,3 let X^i be the co-ordinates of any point P in space, The mathematical description of the state if a moving blood is affected by means of functions which give the distribution of the blood velocity $V^K = V^K(X^i, t)$, k= 1,2,3 and of any two thermodynamic quantities pertaining to the blood, for instance the pressure p = p (X^i , t) and the density ρ = ρ (X^i , t), As is well known, all the thermodynamic quantities are determined by the values of any two of them, together with the equate of state, Hence, if we are given five quantities, namely the three components of velocity V^k, the pressure p and the density ρ , the state of moving blood is completely determined· All these quantities are , in general , functions of the co-ordinates X^i , i=1,2,3 and of the time t, We emphasize that $V^k(X^i$, t) is the velocity of the blood at a given point X^i in space and at a given t, ie it refers to fixed points in space and not to fixed particles of the blood; in the course of time , the latter move about in space.[7]

2.2 – Two Phase Description -

Blood is a complex fluid consisting of particulate corpuscles suspended in a non-Newtonian fluid. The particulate solids are red blood cells (RBCs), white blood cells (WBCs) and platelets. 55% of the plasma and 45% of the blood cells in a whole blood and approximately 98% of RBCs in 45% of blood cells and there are a few parts (approximately 2%) of the other cells[8]. Which are ignorable, so one phase of the bloods plasma and 2nd phase of blood is RBCs [9]

2.3- Constitutive Equations –

Generally blood is non-homogeneous mixture of plasma and blood cells. Though for practical purposes it may be considered to be homogeneous two-phase mixture of plasma and blood cells. The constitutive equations proposed for whole blood mixture are as follows:

1. $\tau = \eta\, e^n$ **when n = 1 then the nature of fluid is Newtonian.[10].**

2. The Non-Newtonian Power Law equation-

$\tau = \eta\, e^n$

2.4- Boundary Conditions are as follows:-

1. The velocity of blood flow on the axis of capillaries at r=0 will be maximum and finite, say V_0 = maximum velocity, V = V_0then A = 0

2. The velocity of blood flow on the wall of coronary capillarirs at r=R, where, R is the radius of coronary capillaries, will be zero. This condition is well known as no-slip condition. V = 0 At r = R

3. Mathematical Modeling-

Let the viscosity of plasma layer be η_p. Let the viscosity of core layer be $\eta_m = \eta_c(X) + (1 - X)\eta_p$ where, η_c is viscosity of blood cells and X is portion of blood cell in unit.

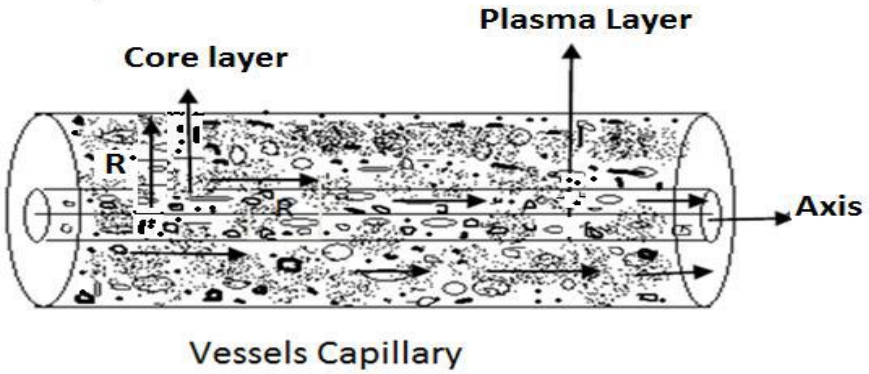


Fig. 3.1

One is Newtonian and other is non-Newtonian

Equation of continuity for power law flow will be as follows:

$$\frac{1}{\sqrt{g}(\sqrt{g}V^i)_{,i}} = 0 \qquad \text{.....(3.1)}$$

$$\rho_m \frac{\partial v^i}{\partial t} + (\rho_m v^i)\, V^i_{,j} = T^{ij}_{,j} \quad \text{.....(3.2)}$$

Where T^{ij} is taken from constitutive equation of per law flow. $\rho_m = X\rho_c + (1-X)\rho_p$ is the density of blood and $\eta_m = X\eta_c + (1-X)\eta_p$ is the viscosity of mixture of the blood. X = H/100 is volume ratio of the blood cell; H is the Hematocrit. Other symbols have their usual meanings.

Since the blood vessels are cylindrical, the above governing equations have to be transformed into cylindrical co-ordinates. As we know earlier:

Now we have to transform the equations (3.1) and (3.2) in cylindrical form. As we know. For cylindrical

$X^1 = r,\ X^2 = \Theta,\ X^3 = z$

Matrix of metric tensor in cylindrical co-ordinates is as follows:-

$$[\, g_{ij}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & r^2 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

While matrix of conjugate matrix tensor is as follow-

$$[g_{ij}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{r^2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Whereas the chritoffel's symbol of 2nd kind are as follow:-

$$\{{}^{1}_{2\,2}\} = -r\,,\ \{{}^{1}_{2\,2}\} = \{{}^{1}_{2\,2}\} = \frac{1}{r}$$

Remaining others are zero.

Relation between contra variant physical components of the blood flow will be as follows:

$$\sqrt{g_{11}}\, v^1 = v_r \implies v_r = v^1$$
$$\sqrt{g_{22}}\, v^2 = v_\theta \implies v_\theta = rv^2$$
$$\sqrt{g_{33}}\, v^1 = v_z \implies v_z = V^3$$

Again the physical components of $p_{,j}g^{ij}$ is $-\sqrt{g_{ii}}\ p_{,j}g^{ij}$

The matrix of the physical components of shearing stress-tensor

$T^{ij} = \eta_m(e^{ij})^n = \eta_m(g^{ik}v^i_{,k} + g^{jk}v^j_{,k})^n$ Will be as follows

$$\begin{bmatrix} 0 & 0 & \eta_m(\frac{dV}{dr})^n \\ 0 & 0 & 0 \\ \eta_m(\frac{dV}{dr})^n & 0 & 0 \end{bmatrix}$$

The covariant derivative of T^{ij}

$$T^{ij}_{,j} = \frac{1}{\sqrt{g}} \frac{\partial(\sqrt{g}T^{ij})}{\partial X^j} + \left\{ {i \atop j\ k} \right\} T^{ij}$$

Keeping in view the above fact, the governing tensorial equation can be transformed into cylindrical form which

Are as follows; the equation of continuity

$$\frac{\partial v}{\partial z} = 0 \quad \text{.....(3.3)}$$

Equation of motion

r – component

$$-\frac{\partial p}{\partial r} = 0 \quad \text{.....(3.4)}$$

$$\Theta = \text{component}, 0 = 0 \quad \text{.....(3.5)}$$

z component

$$0 = -\frac{\partial p}{\partial z} + \frac{\eta_m}{r}\left[r(\frac{\partial V_z}{\partial r})^n\right] \quad \text{.....(3.6)}$$

Here, this fact has been taken in view that the blood flow is axially Symmetric in capillary concerned, i.e.

$$V_\Theta = 0 \text{ and } V_r = 0, \quad \text{.....(3.7)}$$

V_z and p do not depend upon Θ. Also the blood flow steadily, i.e,

$$\frac{\partial p}{\partial t} = \frac{\partial V_r}{\partial t} = \frac{\partial V_\theta}{\partial t} = \frac{\partial V_z}{\partial t} = 0 \quad \text{.....(3.8)}$$

Solution-

On integrating equation (3.3) we get

$V_z = V(r)$ because V does not depend upon Θ

The integrating of equation of motion (3.5) yields:

P = p (z) since p does not depend upon Θ

Now, with the help of equation (3.7) and (3.8) the equations of motion (3.6) convert in the following form

$$0 = -\frac{dp}{dz} + \frac{\eta_m}{r}\frac{d}{dr}\left\{r\left(\frac{dV}{dr}\right)^n\right\} \quad \text{..... (3.9)}$$

The pressure-gradient $-\frac{\partial p}{\partial z} = P$ of blood flow in the capillary can be supposed to be constant and hence the equation (3.8) takes the following form

$$\frac{d}{dr}\left\{r\left(\frac{dV}{dr}\right)^n\right\} = -\frac{pr}{\eta_m} \quad \text{.....(3.10)}$$

On integrating equation (3.10), we get

$$r\left(\frac{dV}{dr}\right)^n = \frac{pr}{2\eta_m} + A \quad \text{..... (3.11)}$$

We know that the velocity of the blood flow on the axis of cylindrical capillary is maximum and constant. So that

We apply the boundary condition at r = 0, v = v_0 (constant), on equation (3.11) takes the following form

$$r\left(\frac{dV}{dr}\right)^n = \frac{pr}{2\eta_m} \Longrightarrow \frac{-dV}{dr} = \left[\frac{pr}{2\eta_m}\right]^{\frac{1}{n}} \quad \text{.....(3.12)}$$

Integrating equation (3.12) once again, we get

$$V = -\left[\frac{P}{2\eta_m}\right]^{\frac{1}{n}} \frac{r^{\frac{1}{n}+1}}{n+\frac{1}{n}} + B \quad \text{..... (3.13)}$$

To determine the arbitrary constant B, we will apply the non-slip condition on the inner wall of the capillary at r = R,

V = 0, where R = radius of vessel, on equation (3.13) so as to get

$$B = \left[\frac{P}{2\eta_m}\right]^{\frac{1}{n}} \frac{nR^{\frac{1}{n}+1}}{n+1}$$

Hence the equation (3.13) takes the following form

$$V = \left[\frac{P}{2\eta_m}\right]^{\frac{1}{n}} \frac{n}{n+1}\left[R^{\frac{1}{n}+1} - r^{\frac{1}{n}+1}\right] \quad \text{..... (3.14)}$$

Which determine the velocity of the blood flow in the capillary where, P is gradient of blood pressure. And η_m is the velocity of blood mixture.

(3.1) Two layered blood flow one layer is Newtonian while the other is Non-Newtonian Power Law-

Now the formula for velocity of blood flows can be obtain by replacing η_m with η_p in of Newtonian model as follows:

$$V_p = \frac{P}{4\eta_p}(R^2 - r^2); R - \delta \le r \le R$$

Where, δ is the radius of core layer.

The velocity of core layer is obtained as the formula of power law model as follows:

$$V_m = \left[\frac{P}{2\eta_m}\right]^{\frac{1}{n}} \frac{n}{n+1}\left[R^{\frac{1}{n}+1} - r^{\frac{1}{n}+1}\right] + \left[\frac{P}{4\eta_p}(R^2 - (R-\delta)^2) - \left(\frac{P}{2\eta_m}\right)^{\frac{1}{n}} \frac{n}{(n+1)}(R^{\frac{1}{n}+1} - (R-\delta)^{\frac{1}{n}+1})\right]$$

$$0 \le r \le R - \delta$$

Where, the 2nd term is the relative velocity of plasma layer with respect to core layer.

(3.2) Bio – Physical Interpretation

Observation: Hematocrit Vs Blood pressure from an authorized City Hospital & Research Centre by Dr. Abhishek Dubey.

Table: Patient case history (Kamla Bai, 55year/female)

Date	Blood Pressure(mmhg)	Hemoglobin (gm %)
04/06/16	110/80	9.5
06/09/19	110/90	10.0
07/09/16	140/100	10.1
09/09/16	120/70	10.5

Hematocrit (H) = 30.0 gm. = 0.0283018867 kg/m^3

$\eta_m = 0.035 \text{pas.sec.}$, $\eta_p = 0.0015 \text{pas.sec.}$ [12]

We know that

$\eta_m = \eta_c X + \eta_p(1 - X)$, where X = H/100

$\Longrightarrow$ η_c = 118.36811 pas.sec.

Again using this relation and change in to the hematocrit

$\eta_m = \eta_c X + \eta_p(1 - X) \Longrightarrow \eta_m$ = 1.1836661309H + 0.0015

Q = 250 ml/m = 0.004166 m^3/s [13]

Length of coronary capillary $\Delta z = 0.1\text{cm.} = 0.001\text{m}$ [14]

Radius of coronary capillary R = 0.0004 cm. = 0.4×10^{-5} m [14]

Blood pressure of capillary = $\left[\frac{\left(\frac{S+D}{2}\right)+D}{3}\right] = \frac{\left(\frac{110/90}{2}\right)+90}{3} = 63.33\text{mmhg}$

Pressure of venules = $\frac{2}{3} \times 63.33 = 42.22\text{mmhg}$

Pressure drop = $p_f - p_i$ = 42.22 - 63.33 = -21.11 mmhg = -2810.41652 pas. Sec.

$\delta = \frac{1}{3}R = \frac{1}{3} \times 0.4 \times 10^{-5} = 0.0133 \times 10^{-4}\text{m.}$

$R - \delta = 0.4 \times 10^{-5} - 0.0133 \times 10^{-4}\text{m.} = 2.67 \times 10^{-6}\text{m.}$

$P = \frac{\Delta p}{\Delta z} = \frac{2810.41652}{0.001} = 2810416.52\text{pas. sec.}$

The flow flux in capillary is

$$Q = \int_0^{R-\delta} \left[\frac{P}{2\eta_m}\right]^{\frac{1}{n}} \frac{n}{n+1}\left[R^{\frac{1}{n}+1} - r^{\frac{1}{n}+1}\right] + \left[\frac{P}{4\eta_p}(R^2 - (R-\delta)^2) - \left(\frac{P}{2\eta_m}\right)^{\frac{1}{n}} \frac{n}{(n+1)}\left(R^{\frac{1}{n}+1} - (R-\delta)^{\frac{1}{n}+1}\right)\right] 2\pi r dr + \int_{R-\delta}^{R} \left[\frac{P}{4\eta_p}(R^2 - r^2)\right] 2\pi r dr$$

$$0.004166 = \int_0^{2.67\times10^{-6}} \left[\frac{2810416.52}{2\times0.035}\right]^{\frac{1}{n}} \frac{n}{n+1}\left[(0.4\times10^{-5})^{\frac{1}{n}+1} - r^{\frac{1}{n}+1}\right] + \left[\frac{2810416.52}{4\times0.0015}((0.4\times10^{-5})^2 - (2.67\times10^{-6})^2) - \left(\frac{2810416.52}{2\times0.035}\right)^{\frac{1}{n}} \frac{n}{(n+1)}\left((0.4\times10^{-5})^{\frac{1}{n}+1} - (2.67\times10^{-6})^{\frac{1}{n}+1}\right)\right] 2\pi r dr + \int_{R-\delta}^{R} \left[\frac{2810416.52}{4\times0.0015}((0.4\times10^{-5})^2 - r^2)\right] 2\pi r dr + \int_{2.67\times10^{-6}}^{0.4\times10^{-5}} \frac{2810416.52}{4\times0.0015}[(0.4\times10^{-5})^2 - r^2)] 2\pi r dr$$

$$0.004166 = (40148807.43)^{\frac{1}{n}}\left(\frac{n}{n+1}\right)\left[(2.67\times10^{-6})\times(2.67\times10^{-6})^{\frac{1}{n}}\left\{\left(\frac{r^2}{2}\right)_0^{2.67\times10^{-6}} - \left(\frac{r^{\frac{1}{n}+3}.n}{3n+1}\right)_0^{2.67\times10^{-6}}\right\}\right] 2\pi \left[(468402753.3) \times \{1.6\times10^{-11} - 7.1289\times10^{-12}\}\left(\frac{r^2}{2}\right)_0^{2.67\times10^{-6}}\right] 2\pi + \left[(468402753.3)\times(1.6\times10^{-11})\left\{\left(\frac{r^2}{2}\right)_{2.67\times10^{-6}}^{0.4\times10^{-5}} - \left(\frac{r^4}{4}\right)_{2.67\times10^{-6}}^{0.4\times10^{-5}}\right\}\right] 2\pi$$

$$0.004166 = (107.1973158)^{\frac{1}{n}}\left(\frac{n}{n+1}\right)\left[\frac{5.97672719\times10^{-17}n + 5.976727182\times10^{-17}}{3n+1}\right] + 9.301416354\times10^{-14} + 5.787273956\times10^{-14}$$

$$0.004166 = (107.1973158)^{\frac{1}{n}}\left(\frac{n}{3n+1}\right)(5.97672719\times10^{-17}) + 1.508869031\times10^{-13}$$

$$6.970370016 \times 10^{13} = (107.1973158)^{\frac{1}{n}} \left(\frac{n}{3n+1}\right)$$

We get n = 0.1366495973

Again we use

$$Q = \int_0^{R-\delta} \left[\frac{P}{2\eta_m}\right]^{\frac{1}{n}} \frac{n}{n+1}\left[R^{\frac{1}{n}+1} - r^{\frac{1}{n}+1}\right] + \left[\frac{P}{4\eta_p}(R^2 - (R-\delta)^2) - \left(\frac{P}{2\eta_m}\right)^{\frac{1}{n}} \frac{n}{(n+1)}\left(R^{\frac{1}{n}+1} - (R-\delta)^{\frac{1}{n}+1}\right)\right] 2\pi r dr + \int_{R-\delta}^{R} \left[\frac{P}{4\eta_p}(R^2 - r^2)\right] 2\pi r dr$$

$$Q = \int_0^{2.67\times10^{-6}} \left[\frac{P}{2\eta_m}\right]^{7.318} (0.12022)[1.2589 \times 10^{-45} - r^{8.318}] + \left[\frac{P}{0.0060}(1.6 \times 10^{-11} - 7.1289 \times 10^{-12}) - \left(\frac{P}{2\eta_m}\right)^{7.318} (0.12022)(1.2589 \times 10^{-45} - 4.363 \times 10^{-47})\right] 2\pi r dr + \int_{2.67\times10^{-6}}^{0.4\times10^{-5}} \left[\frac{P}{0.006}(1.6 \times 10^{-11} - r^2)\right] 2\pi r dr$$

$$Q = \left[\frac{P}{2\eta_m}\right]^{7.318} (9.46570612 \times 10^{-59}) + (5.368851426 \times 10^{-20})P$$

$$0.004166 = \left[\frac{\Delta p}{2 \times \eta_m \times 0.001}\right]^{7.318} (9.46570612 \times 10^{-59}) + (5.368851426 \times 10^{-20})\frac{\Delta p}{0.001}$$

$$0.004166 = \left[\frac{\Delta p}{1.1836661309H + 0.0015}\right]^{7.318} (5.335996163 \times 10^{-39}) + (5.368851426 \times 10^{-20})\frac{\Delta p}{0.001}$$

$(5.368851426 \times 10^{-20})\frac{\Delta p}{0.001}$ (Neglected)

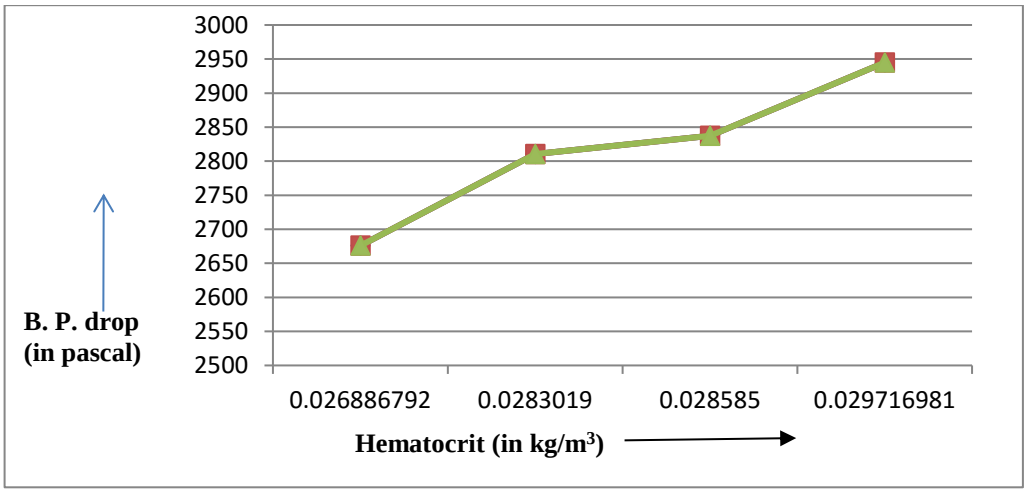
$$(80294.83063) \times (1.1836661309H + 0.0015) = \Delta p$$

$$\Delta p = 95042.271503H + 120.4422459$$

Table for Hematocrit v/s Pressure drop

Hematocrit (kg/m^3)	*0.0268867924*	*0.0283019*	*0.028585*	*0.0297169811*
B. P. drop (in pascal)	*2675.824069*	*2810.3191*	*2837.2166*	*2944.8116319*

Graphical Presentation of clinical data



Graph (i)

We have taken a clinical data of patients who are suffering from angina heart disease. We get a relationship between blood pressure drop and hematocrit for non-Newtonian flow and draw a graph between blood pressure drop and hematocrit, this graph shows from 0.028 to 0.028 the upper convex curve and from 0.028 to 0.0297 lower convex curve.

6- Conclusion-

A simple survey of the graph between blood pressure drop and hematocrit in angina patient shows that when hematocrit is increased the blood pressure drop is also increased.

7- Acknowledgement-

I owe my sincere thanks to Dr. Abhishek Dubey cardiologist of City Hospital and Research Centre at Jabalpur.

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